



**Queensland University of Technology**  
Brisbane Australia

This is the author's version of a work that was submitted/accepted for publication in the following source:

Thiyahuddin, Izzat, Gu, YuanTong, & Thambiratnam, David P. (2012) A coupled SPH/FEM analysis of portable water filled barriers. In *4th International Conference on Computational Methods (ICCM2012)*, 25-28 November 2012, Gold Coast, Qld.

This file was downloaded from: <http://eprints.qut.edu.au/58087/>

**© Copyright 2012 please consult the authors**

**Notice:** *Changes introduced as a result of publishing processes such as copy-editing and formatting may not be reflected in this document. For a definitive version of this work, please refer to the published source:*

## A Coupled SPH/FEM Analysis of Portable Water Filled Barriers

M. I. Thiyahuddin<sup>\*1</sup>, Y.T. Gu<sup>1</sup>, D.P. Thambiratnam<sup>2</sup>

<sup>1</sup>*School of Chemistry, Physics and Mechanical Engineering*

<sup>2</sup>*School of Civil Engineering and Built Environment*

*Queensland University of Technology, Brisbane, Queensland, Australia*

*\*Corresponding author: [mohd.thiyahuddin@qut.edu.au](mailto:mohd.thiyahuddin@qut.edu.au)*

### Abstract

Portable water filled barriers (PWFB) are semi-rigid roadside barriers which have the potential to display good crash attenuation characteristics at low and moderate impact speeds. The traditional mesh based numerical methods alone fail to simulate this type of impact with precision, stability and efficiency. This paper proposes to develop an advanced simulation model based on the combination of Smoothed Particles Hydrodynamics (SPH), a meshless method, and finite element method (FEM) for fluid-structure analysis using the commercially available software package LS-Dyna. The interaction between SPH particles and FEA elements is studied in this paper. Two methods of element setup at the element boundary were investigated. The response of the impacted barrier and fluid inside were analysed and compared. The system response and lagging were observed and reported in this paper. It was demonstrated that coupled SPH/FEM can be used in full scale PWFB modelling application. This will aid the research in determining the best initial setup to couple FEA and SPH in road safety barrier for impact response and safety analysis in the future.

Keywords: SPH, Road Safety Barriers, Coupled Analysis, Impact, Fluid structure interaction, FEA

### Introduction

Portable water filled barriers (PWFB) are moveable roadside delineators that are used on temporary roadside construction area to separate construction site from moving traffic. PWFB is preferred for its portability when empty and becomes heavy when filled with water. PWFB is able to deflect and redirect vehicles at low to moderate speeds. Advanced safety features [1, 2] have been installed in modern cars to ensure driver safety and survivability in the event of a crash. Road safety barriers will need to be at the same level of safety to optimise the chance to save lives.

Water is used in these barriers mainly to increase the overall inertial mass of PWFB to ensure it remains stationary after installation. Pumping and draining of water in the barriers is a tedious task and other aspects are required to ensure practical water management. Currently there are no set regulations on the amount of water required in a barrier. Existing water-filled road barriers weigh approximately 70 kg when empty and can be filled up to 600 kg of water. Furthermore, the energy absorption of water in PWFB has not been established in literature. Prudent water management will allow better optimisation of water resources in road barriers and their response under impact.

This study develops advanced model for smooth transitioning between FEA elements and SPH particles. A model of PWFB made of shell elements was created and filled with SPH particles. The gap between the respective elements was varied, later on the optional shell thickness option was varied to investigate the difference in output. It is most important to ensure there are no lagging at

the boundary of the interacting elements. The relationship of the clearance gap and the optional shell element thickness to the response time between the elements was investigated. The commercially accessible LSTC/LS-Dyna 971 [3] software was used to simulate the model due to its reliable SPH solver. Results were compared to other known similar fluid-structure interaction studies [4, 5].

### **A Coupled SPH/FEM Model**

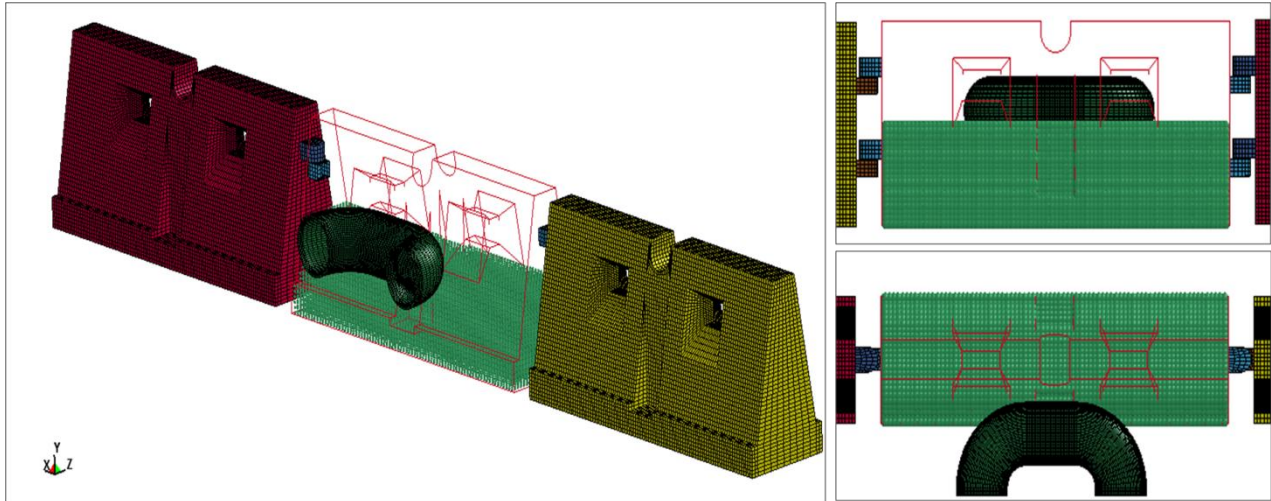
SPH is a meshless computational Lagrangian hydrodynamic particle method. This method originated approximately 30 years ago when it was [6, 7] used to model astrophysical phenomena without boundaries. This method of modelling makes use of particles as the frame for computational interpolation and as carrier of material properties. It has been used in many fields of research including astrophysics, ballistics, vulcanology, solid mechanics and oceanography. The resolution of the method can easily be adjusted with respect to variables such as the density [8] for equal distribution of mass across the SPH region. The SPH system is represented by a finite number of particles that carry individual mass and occupy individual space. SPH is based on interpolation theory by utilising kernel approximation and particles approximation respectively. The conservation laws of continuum dynamics in the form of partial differential equations are transformed into integral equations through the use of an interpolation function for kernel estimation. The main features of SPH were extensively described by Liu [9, 10], Monaghan [11] and Benz [12]. Furthermore, Liu also presented the possibility of SPH being implemented as fluid in the Navier-Stokes equations. Furthermore, The use of coupled SPH/FEM has been shown to have potential to replicate water in a scaled analysis[13].

SPH suffers from the implementation of finite boundary conditions. On the other hand, FEA method is not able to replicate high rate of deformations that are seen in fluid materials. The use of FEA elements as boundaries for SPH particles provides a possible solution to observe the sloshing effect of fluids for better numerical solutions. Using the advantages of both methods, it is possible that coupled analysis utilising both parts be able to model accurately the impact of a PWFB. The research employs the use of coupled SPH/FEM elements in the simulation. The SPH particles are given properties for water and the FEA shell elements were used to for the barrier's shell. Model of a current road barrier provided by the industry partner was designed and meshed. Then, simulations were done and results of the simulation were scrutinised.

In the model, initial element setup is important to ensure a smooth transition between FEA elements and the SPH particles. Using the commercially available software LS-Dyna v971, the user is able to arbitrarily choose the initial clearance between the particle and elements. The clearance between SPH particles and elements must be close enough to achieve steady interface but far enough to avoid unphysical penetration and system instability. This presses the need to establish setup guidelines for future analysis involving coupled SPH/FEM elements in impact analysis. The finite element meshed was created and SPH particles were introduced into the model using the shell volume method for SPH generation. The clearance gap between the elements and particles were varied from 0mm, 3mm, 5mm to 10mm. Then, the impact responses of the SPH particles subjected to the impact conditions were obtained. Simulations were conducted using Fluid Particle Approximation with Renormalized Particles (IFORM=6) method with initial smoothing length of 1. The smoothing length is left default to vary between 0.8 to 1.2mm depending on the computer's calculation. Moreover, the use of optional shell thickness for smooth transitioning was also explored and the best possible contact condition is chosen. The optional thickness was varied from 0mm, 0.1mm, 0.5mm 2mm and 4mm relative to its original thickness of 8mm. The best outcome

that has system stability with no particle penetrations and optimal computational time was observed and reported.

The setup for the model is illustrated in the Figure 1. The entire simulation is consisted of shell elements, solid elements and SPH particles.



**Figure 1: Overview of Model**

The barrier model consisted of three aligned barriers in a row. The barrier is made of shell elements and has 47,581 elements with 20mm edge length. The adjacent barriers were left empty but were assigned a single element mass of 400kg. This is similar to the amount of mass of a barrier filled at half capacity. The material property of the shell element is assigned MAT\_PIECEWISE\_LINEAR\_PLASTICITY of High Density Polyethylene (HDPE) available in literature.

The SPH particles were created inside the barrier in the middle of the row. The fill level is done at minimum fill level of 50%. With equal distance of 25mm between particles at all axes, it takes 27,124 particles to fill half of the empty barrier. The SPH particles were assigned MAT\_NULL and properties of water were inputted with the Mie-Gruneisen equation of state.

The rigid impact head were assigned with MAT\_RIGID property and consist of 6,512 solid elements. The impact head had an initial velocity of 8m/s in a single direction for purpose of impact. There are no friction between the barrier and the ground since this study focused on the interaction of the coupled SPH/FEM elements. The simulation's responses of the SPH particles at different clearance gap and shell thickness were extracted. The simulations used AUTOMATIC\_NODE\_TO\_SURFACE contact conditions with the shell element as master and SPH particles as slave nodes for fluid-structure interaction.

In order to appropriately apply coupled SPH and FEA analysis, several issues need to be tackled to streamline the interaction of meshed and meshless elements in the model. In this research, SPH particle discretisation is dependent on the shape of the volumetric shell it is enclosed in. There are currently no set of rules for proper initial position setup of each particles and elements in the model. In addition, contact definition at the interface between the particles and finite element section must be defined accordingly to achieve agreeable solution.

## **Contact Region of Coupled SPH/FEM**

There are several methods to define the contact boundary between the elements involved. The “nodes\_to\_surface” contact were employed in all the simulations with the shell elements as the master and SPH particles as the slave nodes [3, 14]. The research explores the use of clearance gap and optional thickness in the contact boundary section of LS-Dyna. There are several ways to create boundary conditions such as the use of ghost particles [15, 16] or boundary transition region technique[17] but they will not be covered in this paper.

The clearance gap tab in the shell volume SPH generation option allows the user to specify an arbitrary initial space between the SPH particles with its nearest FEA elements. This provides a consistent distance that will allow system stability during the initial stages of analysis. Other advantage of setting a clear gap between the elements is to allow specific room of movement for one part to move before interacting with the other. On the other hand, the distance may cause a lagging effect while transitioning from FEA elements to the SPH particles.

Another method that can be employed is the Master/Slave initial thickness option [3]. This permits the user to overwrite the thickness of the shell elements without having to specify a gap between the coupled elements. Furthermore, adding an optional thickness to a master part will permit multiple slave parts to interact differently for each of its contact purposes. Thus, this method allows smooth transitioning between the elements but the occurrence of unphysical penetration of particles may become extensive in the simulation.

## **Parametric studies**

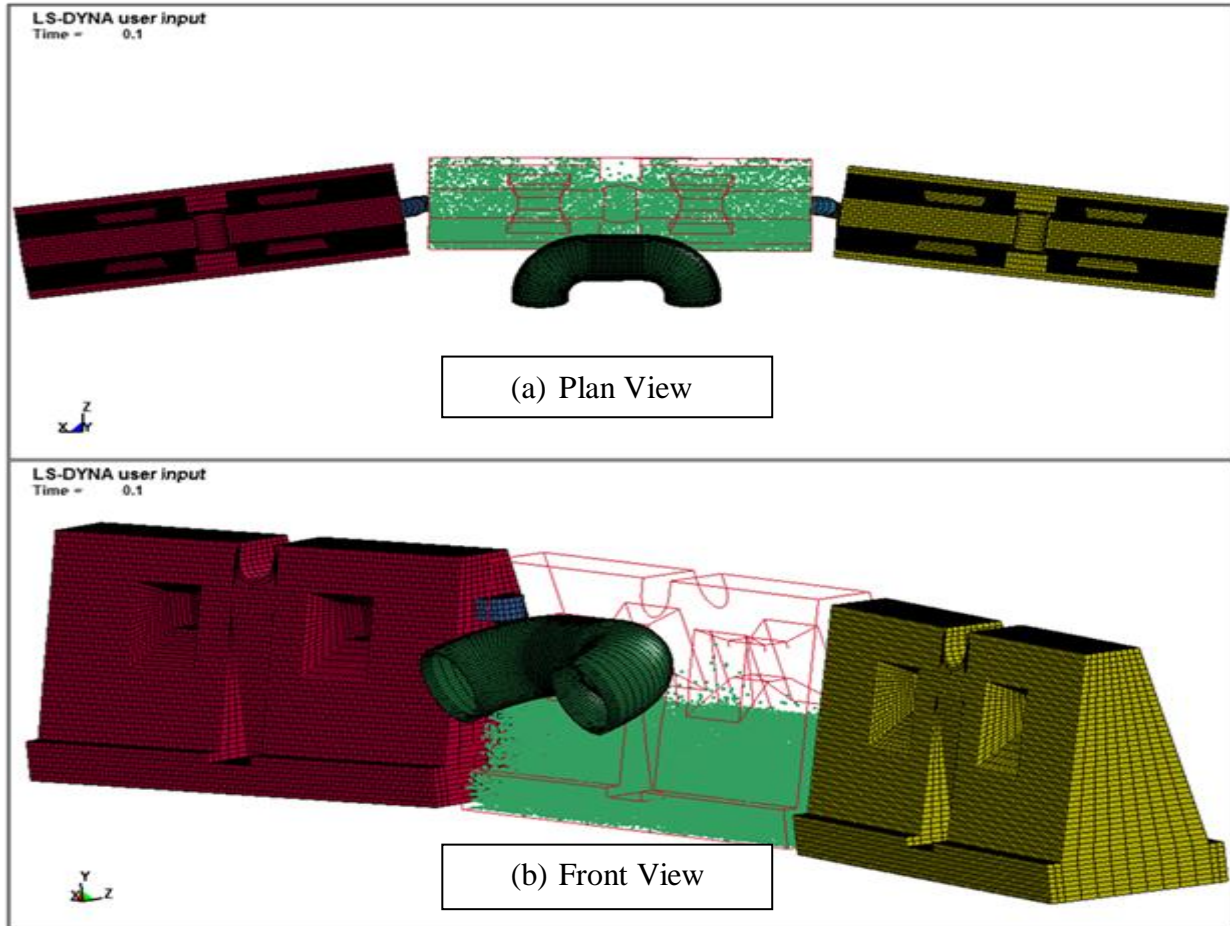
### **I. Optional Shell Element Thickness**

The element thickness of the barrier was 8mm. The optional shell element thickness option allows the user to input different thickness of the element shell. For this case, the optional element thickness is less than the shell element thickness. The element thickness was varied from default 0mm, 0.1mm, 0.5mm, and 2mm till 4mm. The option card is useful if multiple interactions exist in a single part e.g. the barrier's shell.

It is observed that the optional shell thickness does not affect the structural output of the simulation as all the barriers recorded same level of stresses on impact. Without a set clearance gap between the particles, the computational time of the simulation significantly increased with no significant difference in output. The increase in time is caused of the system was trying to stabilise itself by offsetting the initial contact penetration between SPH particles and FEA elements. The use of optional thickness cancels out the offset created by the projected contact surface which is half of the shell thickness in LS-Dyna. It is possible to scale back the optional thickness but too small of a contact thickness will lead to contact failure. Therefore the use of optional thickness is not advisable due to the susceptibility of the model to become unstable which will lead to interpenetrations.

## II. Study of Clearance Gap

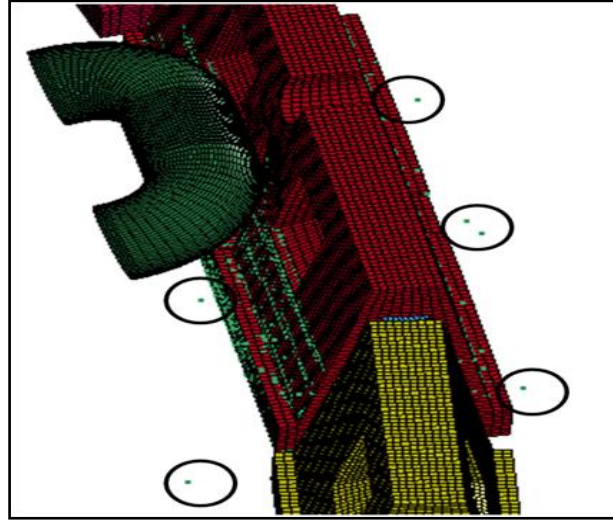
Reiterations were done with different clearance gap and thickness shell elements as well as shell formulations.



**Figure 2: Plan and Front view of impacted barriers at 0.1s**

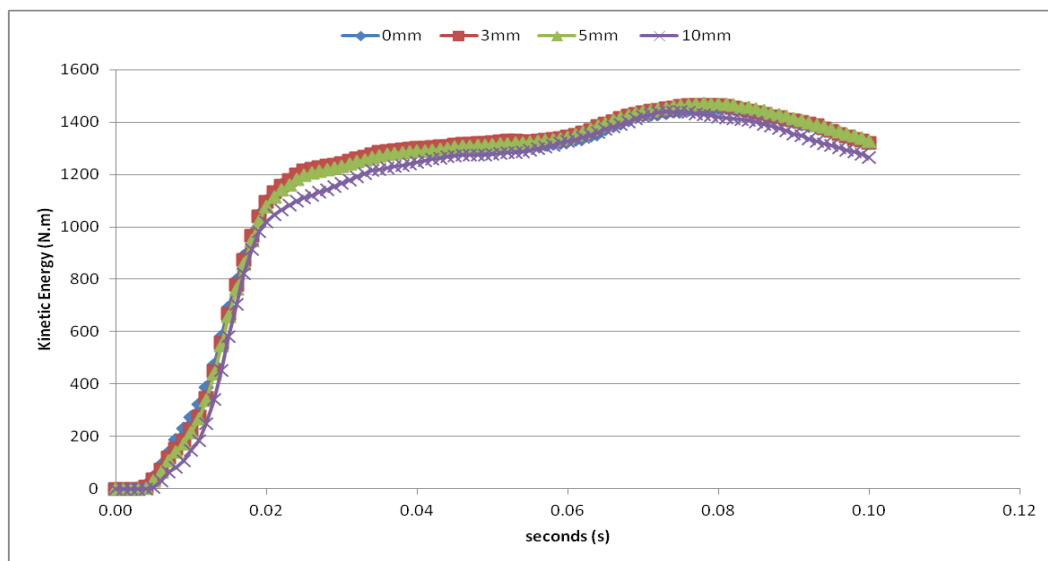
Figure 2 shows the acceptable result in simulation. The SPH particles interacted with the FEA elements and remained inside the enclosed boundary of the shell. The steady interaction between shell elements and SPH particles is of utmost importance to allow smooth energy transmission. The sloshing of water can be seen clearly in the model. Ideally, the distance is a compromise between system response and lagging. Having a wide space from FEA elements to SPH particles will allow stability in the system but creates the possibility of energy transfer lag at the boundary between the elements. On the other hand, narrowing the distance will increase the system sensitivity of the movement but increases the possibility of unphysical penetration of particles through the shell elements as circled in black in Figure 3. It was observed that the larger the initial gap between the SPH particles and the FEA elements, the more stable the system is from penetrations. In other words, models that have smaller gaps between the coupled elements are more likely to suffer system instability. Penetrations and negative energies were not detected at the beginning phase, but are evident later in the simulation. This prompted the use of damping treatment and artificial viscosities to smear the effect of high particles shocks.





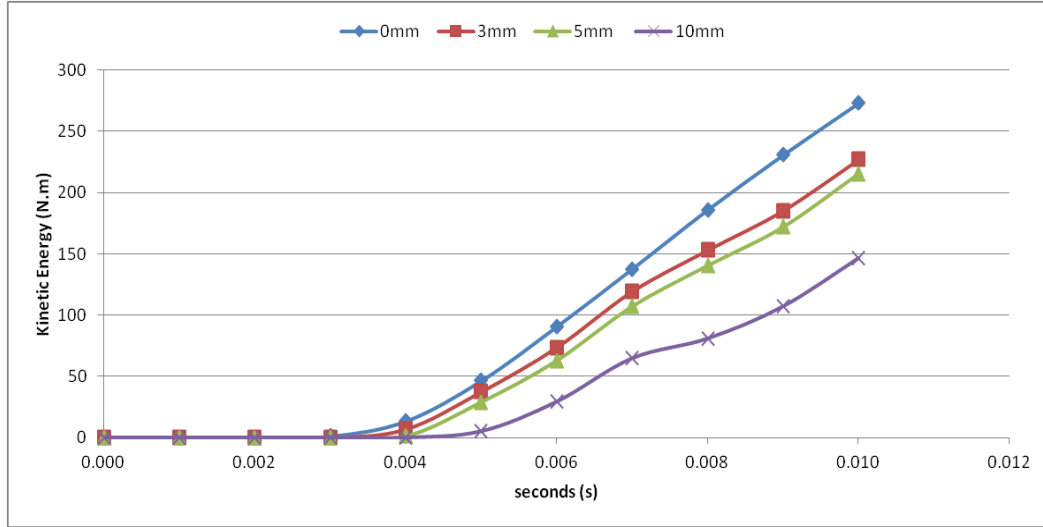
**Figure 3: Unphysical Penetration that occurs in the system**

Figure 4 shows the kinetic energy transfer for all the simulation with clearance gap of 0mm, 3mm, 5mm and 10mm. It shows the kinetic energy experienced by SPH particles at different times. It can be seen that the biggest clearance gap i.e 10mm suffers from system energy lag. Furthermore, focusing the SPH particles response between  $0 < t < 0.01$ s in Figure 5, it can be seen that the 10mm clearance gap is trailing compared to others which in turn will affect the accuracy of the model.



**Figure 4: Kinetic Energy of SPH particles at  $0 < t < 0.1$**

In Figure 5, it can be seen at the beginning the kinetic energies of all the models are same at 0s. After impact, the kinetic energy diverged depending on the proximity to the shell elements. The most significant discrepancy can be seen between 0mm and 10mm clearance gap.



**Figure 5: Kinetic energy at  $0 < t < 0.01s$**

With the results shown in Figure 5, for shell element thickness of 8mm; it is recommended that the clearance gap would be between 3mm and 5mm. It can be inferred that the gap of 3mm is the best due to the fact that it increases in parallel with 0mm and the lag is close enough to be negligible. This distance is ideal because the clearance proximity distance provide enough space for the projection vector to detect the particle nodes with no loss as seen in 10mm distance.

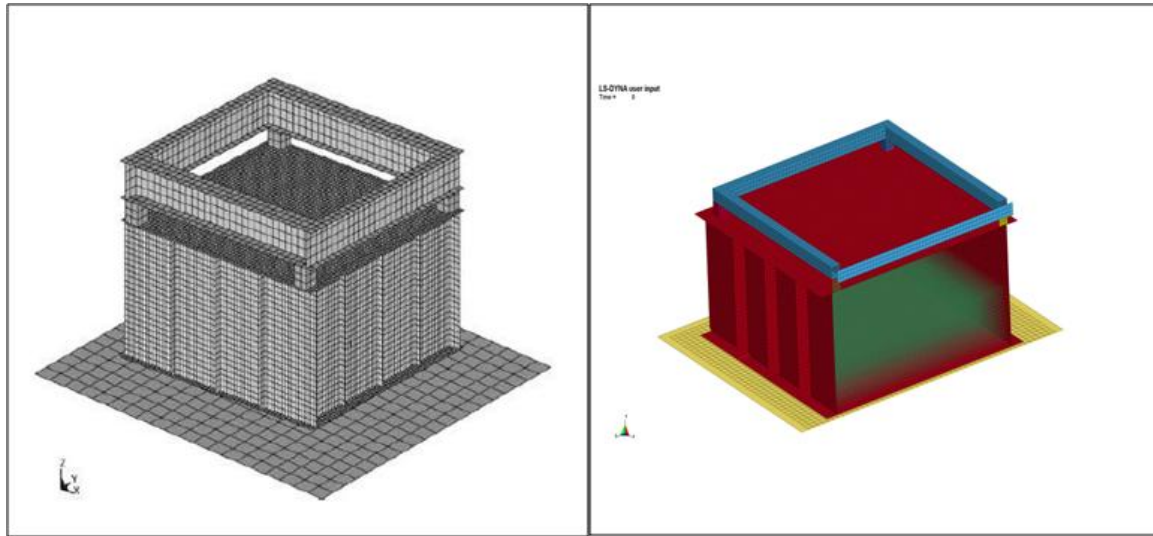
The contact problem arises from the shell element side of the model rather than the particle side. Having a coarse finite element mesh will open the possibility to particle interpenetrations during simulations. Therefore, to couple FEM with SPH particles, the meshed element size is recommended to be the same as the distance between SPH particles.

The projected contact surface vector (which is half of the shell thickness) that exists in the shell elements is the reason behind the need to specify gap in the system. By using the clearance gap option, the user can properly offset the adjacent SPH particle node to account for the part thickness during the SPH particle generation phase. It is worth to note this phenomenon also occurs on contact between 2 meshed finite element parts. The extra space between the particles will allow the shell elements to detect the SPH particles at the beginning of the simulations with slight compromise on the sensitivity at the boundary region. This will prevent initial contact interpenetrations in the system.

### III. Analysis of Coupled Technique

Based on the parameters varied in Sections I and II, the recommendation to implement the technique is put to the test. A replica model of Anghileri et al.[4] tank was created but the SPH particles were generated using shell volume method instead of the method which Anghileri used. Different clearances were placed in the model and system stability is monitored. Additional use of bulk viscosity, large damping coefficient and explosive time step controls were employed to treat shock discontinuities due to the high velocities that exist in the model. This had not been employed previously due to the lower speeds tested in the road barriers. Results of the fully compliant steady model were then compared against results found in the original studies.





**Figure 6: Model of tank by Anghileri (left) and model of tank used in this study (right)**

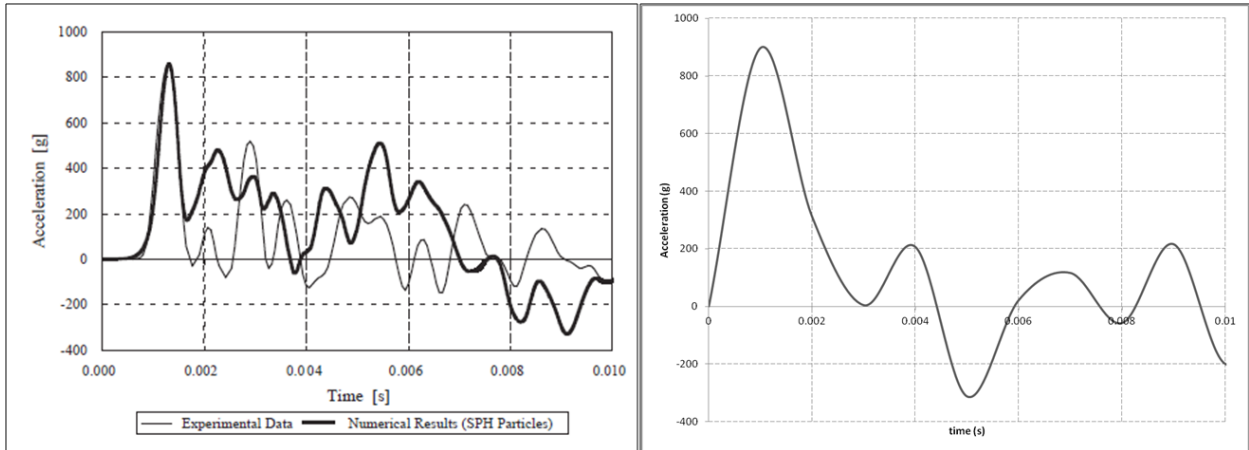
In the initial analysis, the particle distance was left constant at 5mm and the impact velocity was varied. The number of particles penetrating the shell surfaces were observed and recorded. The tabulated data of the observation is listed in Table 1 below.

**Table 1: Impact Velocity and Penetrating Nodes Observed**

Impact Speeds (m/s)	Quantity of penetrating nodes
3	0
6	1
8	6
12	10

There were no initial penetration in the system but as the simulation proceeded, it was observed that more particles started to penetrate the boundary as the speed is increased. The penetration that occurs at stages after the simulation began is caused by discontinuities in the Hugoniot line due to the emergence of shocks in the system. The contact algorithm was unable to properly conduct interaction of the shell and individual particles due to the velocity of the specific particles being too high. Thus, the shell surface failed to detect the particle which resulted in several runaway particles. This issue can be treated with the proper application of bulk viscosities parameter, huge damping coefficients and smaller time step; all of which are introduced solely to smear the shock effects in order to stabilise the system. However, the control treatment dampens the sloshing effects in the system which dilutes the actual dynamics of the event.

The next analysis of the system involved varying the initial particle distance from 0mm to 10mm with an unchanged impact velocity of 12m/s and all damping treatment was left unchanged in the models. Any unphysical penetrations were monitored and compared with known results from [4]. Based on obtained results shown in Figure 7, as the distance between the coupled elements gets farther from each other, the system becomes more stable to run. At a distance of 10mm, the results were in agreement with results obtained by Anghileri et al.



**Figure 7: Comparison of the acceleration between Anghileri[4](left) and results from this study (right)**

## Discussions

SPH particles performed remarkably in demonstrating the sloshing phenomenon that occurred in the barrier under impact. FEA alone is not able to replicate high level of deformations exhibited by water in high impact situations.

In general, this study examined ability of the shell elements to retain the particle within a finite boundary edge. Several points must be addressed if this technique is adopted into road barrier simulations. Firstly, the element proximity must be near enough to permit direct transition of energy from FEA elements to SPH particles, vice versa, but far enough for stability in the system. Secondly, the distance plays a pivotal role in determining the response time of SPH particles. The shell thickness option provides the ability to input optional thickness that will not interfere with other contact conditions in the setup. For example, adding an optional thickness on the contact conditions between the shell elements and SPH particles will not affect the overall performance of the barrier contact with the impact head. Thirdly, the speed involves in the analysis affects the ability of the SPH/FEM coupling to a certain extend. At higher speeds involving fluids, the researcher must anticipate the present of shocks in the analysis by properly assigning fluid particles position to be at least one half the thickness of the shell elements.

## Conclusions

The simulations demonstrated the ability of SPH/FEM to explore the characteristics of water under impact loading inside a road safety barrier. Based on the results obtained in the study, the correct proximity between FEA elements and SPH particles is important to ensure system stability. The clearance gap is best to be at least one half of the actual shell thickness element. Furthermore, additional controls are needed to inhibit penetrations at higher speeds as can be seen in Section III.

In conclusion, the clearance gap option is a preferred choice when setting up SPH particles for coupled analysis in LS-Dyna. Element discretisation is important especially if the simulation involves multiple slave sections reacting to a single master part. Further study that can be conducted would be to investigate the systems' stability at higher impact speeds. This is useful to determine the validity of the coupled SPH/FEM method and threshold value of reliability of this technique at higher impact shocks to study fluid-structure interactions. The researcher must also take into consideration the speed in the study to allow enough space to couple SPH/FEM in road barrier studies.

## Acknowledgement

This work is supported by an ARC Linkage Grant (LP1020318). Suggestions and the contribution of the Industry Partner, Centurion Barrier Systems, are acknowledged.

## References

- [1] G. M. Nagel and D. P. Thambiratnam, "A numerical study on the impact response and energy absorption of tapered thin-walled tubes," *International Journal of Mechanical Sciences*, vol. 46, pp. 201-216, 2004.
- [2] Z. Ahmad and D.P. Thambiratnam, "Application of foam-filled conical tubes in enhancing the crashworthiness performance of vehicle protective structures," *International Journal of Crashworthiness*, vol. 14, pp. 349-363, 2009.
- [3] J. Hallquist, "LS-DYNA. Keyword user's manual. version 971," *Livermore software technology corporation*, 2007.
- [4] M. Anghileri, L-M. L Castelletti, M. Tirelli, , "Fluid-structure interaction of water filled tanks during the impact with the ground," *International Journal of Impact Engineering*, vol. 31, pp. 235-254, 2005.
- [5] M. Anghileri L-M. L Castelletti, E. Francesconi, A. Milanese, M. Pittofrati, "Rigid body water impact-experimental tests and numerical simulations using the SPH method," *International Journal of Impact Engineering*, vol. 38, pp. 141-151, 2011.
- [6] L. Lucy, "A numerical approach to the testing of the fission hypothesis," *The Astronomical Journal*, vol. 82, pp. 1013-1024, 1977.
- [7] R. A. Gingold and J. J. Monaghan, "Smoothed particle hydrodynamics-theory and application to non-spherical stars," *Monthly Notices of the Royal Astronomical Society*, vol. 181, pp. 375-389, 1977.
- [8] R. F. Stellingwerf and C. A. Wingate, "Impact Modelling with Smooth Particle Hydrodynamics," *Societa Astronomica Italiana*, 1994.
- [9] M. B. Liu and G. R. Liu, "Smoothed particle hydrodynamics (SPH): An overview and recent developments," *Archives of Computational Methods in Engineering*, vol. 17, pp. 25-76, 2010.
- [10] G. R. Liu and M. B. Liu, *Smoothed particle hydrodynamics : a meshfree particle method*. New Jersey: World Scientific, 2003.
- [11] J. Monaghan, "Smoothed particle hydrodynamics," *Reports on Progress in Physics*, vol. 68, p. 1703, 2005.
- [12] M. S. Fulbright, W. Benz, M.B Davies, "A method of smoothed particle hydrodynamics using spheroidal kernels," *The Astrophysical Journal*, vol. 440, pp. 254-262, 1995.
- [13] I. Thiyahuddin, Y.T Gu, D.P. Thambiratnam, P. Gudimetla, "Impact & energy absorption of road safety barriers by coupled SPH/FEM," *International Journal of Protective Structures*, vol. 3, p. 16, 11/09/2012 2012.
- [14] Y. T. Gu and G. R. Liu, "Meshless Methods Coupled with Other Numerical Methods," *Tsinghua Science & Technology*, vol. 10, pp. 8-15, 2005.
- [15] M. B. Liu, G. R. Liu, K. Y Lam, Z. Zong, "Smoothed particle hydrodynamics for numerical simulation of underwater explosion," *Computational Mechanics*, vol. 30, pp. 106-118, 2003.
- [16] M. B. Liu, G. R. Liu, K. Y Lam, Z. Zong, "A new technique to treat material interfaces for smoothed particle hydrodynamics," *Computational Mechanics - New Frontiers for New Millennium*, pp. 977-982, 2001.
- [17] Y. T. Gu and L. C. Zhang, "Coupling of the meshfree and finite element methods for determination of the crack tip fields," *Engineering Fracture Mechanics*, vol. 75, pp. 986-1004, 2008.